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A life cycle assessment study of a Canadian post-combustion carbon dioxide capture process system

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Abstract
Purpose While carbon dioxide capture and storage (CCS) has been widely recognized as a useful technology for mitigating greenhouse gas emissions, it is necessary to evaluate the environmental performance of CCS from a full life cycle perspective to comprehensively understand its environmental impacts. The primary research objective is to conduct a study on life cycle assessment of the post-combustion carbon dioxide capture process based on data from SaskPower's electricity generation station at the Boundary Dam in Saskatchewan, Canada. A secondary objective of this study is to identify the life cycle impact assessment (LCIA) methodology which is most suitable for the assessment of carbon dioxide capture technology integrated with the power generation system in the Canadian context.
Methods The study takes a comparative approach by including three scenarios of carbon dioxide capture at the electricity generation station: no carbon dioxide capture ("no capture"), partial capture ("retrofit"), and fully integrated carbon dioxide capture of the entire facility ("capture"). The four LCIA methods of EDIP 97, CML2001, IMPACT2002+, and TRACI are used to convert existing inventory data into environmental impacts. The LCIA results from the four methods are compared and interpreted based on midpoint categories.
Results and discussion The LCA results showed an increase in the retrofit and capture scenarios compared to the no capture scenario in the impact categories of eutrophication air, ecotoxicity water, ecotoxicity ground surface soil, eutrophication water, human health cancer ground surface soil, human health cancer water, human health noncancer ground surface soil, ozone depletion air, human health noncancer water, and ionizing radiation. The reductions were observed in the retrofit and capture scenarios in the impact categories of acidification, human health criteria air-point source, human health noncancer air, ecotoxicity air, global warming, human health cancer air, and respiratory effects.
Conclusions Although the four LCIA methodologies significantly differ in terms of reference substances used for individual impact categories, all (TRACI, IMPACT2002+, CML2001, and EDIP 97) showed similar results in all impact categories.

Keywords Carbon dioxide (CO_2) post-combustion capture · CML2001 · EDIP 97 · IMPACT2002+ · Life cycle impact assessment (LCIA) · Midpoint approach · TRACI

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1 Introduction

Carbon dioxide capture and storage (CCS) has been recognized as an important approach for reduction of industrial greenhouse gas emissions. As the coal-fired electricity generation station is a significant source of carbon dioxide (CO_2) and other emissions, the integration of CO_2 capture technology can substantially reduce CO_2 and other emissions such as sulfur oxides, nitrogen oxides, and heavy metals. However, it

must be recognized that utilization of CO_2 capture technology presents two major challenges. First, it significantly decreases electricity generation efficiency, and hence, a larger amount of coal is needed to compensate for the lost capacity. Secondly, resource use and environmental impacts that result from construction, operation, and decommissioning of a CO_2 capture facility need to be considered. Due to these challenges, it is necessary to conduct a life cycle assessment of an electricity generation station with CO_2 capture so as to evaluate its overall environmental performance. It is also important to understand the full ramification of the process if comparisons are to be made to other alternative technologies for greenhouse gas (GHG) emission reduction.

In order to evaluate environmental performance of an electricity generation station with CO_2 capture from a full life cycle perspective and gain a better understanding of the implications of CO_2 capture operations, a life cycle assessment (LCA) study of SaskPower's Clean Coal project at the Boundary Dam Power Station (BDPS) in Saskatchewan, Canada was conducted. The system under study consists of an 882-MW_e lignite coal-fired electricity generation station with a CO_2 post-combustion capture unit.

The study took a cradle-to-gate approach which included the processes of coal mining, electricity-generating station construction, operations and decommissioning, and the CO_2 capture unit construction, operation, and decommissioning. Three scenarios were studied:

1. Electricity generation station without capture (hereafter referred to as "no capture")
2. Retrofit of only one 150-MW_e unit with flue gas desulfurization (FGD) and CO_2 capture ("retrofit")
3. Electricity generation station with FGD and CO_2 capture on all six units ("capture")

The processes within the system boundaries were modeled in the LCA software of GaBi4. Four different life cycle impact assessment methods were applied and evaluated, which include EDIP 97, CML2001, IMPACT2002+, and TRACI. These life cycle impact assessment (LCIA) methods provide different mechanisms to translate the life cycle inventory data, i.e., data on environmental load, inputs and outputs, into environmental impacts.

This paper compared and discussed the four different LCIA methods and applications of the methods to the data generated from the BDPS. The paper also provided some suggestions for an LCIA methodology best suited to the Canadian environment.

The paper is organized as follows. Section 2 provides a literature review of the four LCIA methodologies applied in this study. Section 3 defines the goal and scope of the study and presents the life cycle impact assessment results. Section 4 discusses the strengths and limitations of the LCIA methodologies based on their applications to the electricity generation station with post-combustion CO_2 capture. Section 5 presents the conclusions and recommendations for future work.

2 Literature review

2.1 Life cycle impact assessment methods

After conducting a review of the LCIA methodologies, it was found that the following five LCIA methodologies are most comprehensive and commonly used. These are EDIP 97/2003, EcoIndictor99, TRACI, IMPACT2002+, and CML2001. While EDIP 97/2003, TRACI, IMPACT2002+, and CML2001 are midpoint-based methodologies, EcoIndicator99 is a damage-oriented method, which assesses the environmental impacts based on the endpoint categories. Hence, the four methods of EDIP 97/2003, TRACI, IMPACT2002+, and CML2001 were applied in this study since the results can be compared in terms of the midpoint categories. These four midpoint-oriented methods are summarized in Table 6. The four methodologies are all supported in the software adopted for this study, which is GaBi 4.4. Since the ReCiPe methodology is not supported by this software, it was not applied. More details on how the form LCIA methods define the categories of human toxicity impact categories and midpoint reference substances can be found in the Electronic Supplementary Material (ESM). Table 1 in the ESM shows the comparison for the human toxicity impact categories, and Table 2 in the ESM shows the comparison for the midpoint reference substances.

2.2 Literature review of past LCA studies

LCA studies have been widely applied to pulverized coal, integrated gasification combined cycle, and natural gas combined cycle electricity generation systems. These power-generating systems are usually integrated with different CO_2 capture technologies such as post-combustion, pre-combustion, and oxy-fuel. Since this paper deals with the post-combustion CO_2 capture, this section provides an overview of some studies related to LCA of the post-combustion CO_2 capture process system. Koornneef et al. (2008) presented a comparative LCA on a conventional subcritical pulverized electricity generation plant, an ultra-supercritical pulverized electricity generation plant, and an ultra-supercritical pulverized electricity generation plant integrated with a monoethanolamine (MEA)-based post-combustion CO_2 capture system. The CML2001 method was used in this study to characterize and evaluate the environmental impacts of these processes. Schreiber et al. (2009) conducted a comparative LCA in GaBi 4.2 to assess the environmental and human health impacts of electricity generation from five pulverized coal-fired electricity generation plants with MEA-based post-combustion CO_2 capture and those without CO_2

capture. The characterization of environmental impacts is based on the CML2001 method. Pehnt and Henkel (2009) presented a comparative LCA study on three CCS technologies applied to several lignite-generating plants from a full life cycle perspective. The life cycle included lignite mining and transportation, plant construction and decommissioning, and CO_2 transportation and storage in a depleted gas field. The CML1992 method was used to characterize and evaluate the environmental impacts of these processes. Nie et al. (2011) carried out a life cycle assessment of various CO_2 capture technologies by modeling unit processes in the plants. Both post-combustion and oxy-fuel power generation with CO_2 capture, transport, and injection processes were studied. The CML2001 methodology was employed for the LCIA. Singh et al. (2011) compared and evaluated various coal and natural gas electricity generation plants with the three types of CO_2 capture technologies of post-combustion capture with amine-based absorption, pre-combustion capture with Selexol absorption, and oxy-fuel combustion capture. Their research was based on the life cycle inventory (LCI) data derived from the Ecoinvent v2 database (Althaus et al. 2004), and the ReCiPe2008 method was applied.

3 Methods—LCA study of post-combustion CO_2 capture

3.1 Goal and scope definition

This study aimed to evaluate the life cycle of the electricity generation station with and without CO_2 capture by applying different LCIA methodologies to the lignite coal-fired electricity generation plant with post-combustion CO_2 capture. Saskatchewan Power Corporation's (SaskPower) BDPS in Estevan, Saskatchewan was chosen as a case study and operations at the electrical generating station of BDPS were modeled. BDPS is a lignite coal-fired electricity generation plant, which consists of six units equipped with electrostatic precipitators; the plant generates a gross electricity capacity of 882 MW. The composition of lignite coal used in BDPS is listed in Table 1, and the heating value of lignite coal is 15,119 kJ/kg.

The amount of lignite coal needed to produce the gross electric capacity of 882 MW was calculated based on the gross cycle heat rate and higher heating value of coal (Table 3). The amount of oxygen needed for stoichiometric combustion of fuel is the sum of oxygen needed to convert carbon to carbon dioxide, hydrogen to water, and sulfur to sulfur dioxide minus any oxygen in fuel. The combustion products were calculated using emissions factors for pulverized coal tangentially fired dry bottom boilers. The information was extracted from the U.S. Environmental Protection Agency report for lignite coal combustion and the emissions factors are summarized in Table 2. More detailed information can be found in Manuilova (2011).

A retrofit of one of the units of the BDPS, namely, unit 3 with a generating capacity of 150 MW, was analyzed in the study. The retrofit included installation of the wet FGD unit and the post-combustion CO_2 capture unit. This operation is described as the retrofit scenario in this study. In the capture scenario, the FGDs and CO_2 capture units have been installed on all six units of the electrical generating station (Table 3).

The wet flue gas desulfurization unit has been installed to remove SO_2 before the flue gas enters the CO_2 capture unit, in which the post-combustion amine-based absorption of CO_2 from flue gases and CO_2 compression was modeled and 30 wt% MEA was used as the sorbent. The system consists of two main components: (1) an absorber, where CO_2 is absorbed into a sorbent, and (2) a regenerator (stripper), where CO_2 is released in concentrated form and the original sorbent is recovered. The modeling assumptions are presented in Tables 4 and 5.

This was a cradle-to-gate study. The environmental performance of the following three scenarios was compared:

1. The electricity generation plant without CO_2 capture (no capture)
2. Retrofit of one unit (150 MW_e) with flue gas desulfurization and CO_2 capture unit (retrofit)
3. The electricity generation plant with FGD and CO_2 capture on all six units (capture)

3.1.1 Functional unit

The functional unit corresponds to the reference flow where all flows and data of the system (i.e., energy, materials, emissions, and wastes) are normalized. The main function of the system under study was to produce electrical energy. The functional unit for this study was megawatt hour of electricity produced. Since the energy used for CO_2 capture and compression was assumed to come from the electricity generation station, therefore, the net energy output from the plant was reduced. Since all the scenarios in the study generate the same electricity, it was assumed that the electricity production and CO_2 capture rate were constant. However, since scenarios 2 and 3 describe the CO_2 capture facilities, they actually involve a higher level of coal consumption for producing the same net amount of electricity.

3.1.2 System boundaries

The system boundary defines the unit processes included in the system under study. This was a cradle-to-gate study that included all life cycle activities from resource extraction (e.g., coal, limestone, and iron) and production of materials (e.g., steel, concrete, MEA) through the generation of electrical energy at the electricity generation station with and without

Table 1 Composition of lignite coal

Parameter	Moisture	Carbon	Hydrogen	Nitrogen	Sulfur	Ash	Oxygen	Mercury	Chlorine
Unit	%	%	%	%	%	%	%	ppb	ppm
Value	35.00	41.70	2.61	0.79	0.54	9.47	9.90	79.00	10.20

the CO_2 capture process. The system boundary of this study is presented in Fig. 1.

Temporal and geographical boundaries The temporal boundary was defined as 30 years, and it was assumed for the purpose of this study that plant construction would be completed by 2015. This duration included the time needed for coal mining, plant construction, commissioning, and operation. The data for most of the processes included within the system boundaries were generated in Western Canada. However, the data for some unit processes were taken from plants in other Canadian provinces, the USA, and other countries.

Technological boundaries This study evaluated the modern post-combustion CO_2 capture technology and the well-established configuration used for generation of electrical energy.

3.2 Life cycle inventory data quality, sources, and assumptions

The LCI data came mostly from Manuilova (2011) and Suebsiri (2010). The majority of the data were specific to Western Canada. In the absence of data from Western Canadian sources, information was taken sequentially from (a) other Canadian sources, (b) North American sources, (c) European sources, and (d) existing life cycle databases, most notably from Ecoinvent v2.1. Other sources of data included, but were not limited to, SaskPower, Stantec, International Test Centre for CO_2 Capture, Intergovernmental Panel on Climate Change, Environment Canada's National Greenhouse Gas Inventory and relevant scientific publications. All data adhered to the specifications listed in the 2006 ISO 14040 (2006) and ISO 14044 (2006) standards. For example, data on electricity generation station construction per 1 MW of plant capacity was extracted from Spath et al. (1999); the MEA production dataset was adapted from Althaus et al. (2004) and Koornneef et al. (2008).

Table 2 Emission factors for lignite combustion in pulverized coal-fired dry bottom boilers, kilograms per tonne of coal

PM	PM10	NO	NO_2	HCI	HF	CH4	Total VOC
3.2A	1.15A	0.95×3.16	0.05×3.16	0.6	0.075	0.02	0.02

Where A is ash content in coal (fraction)

3.3 Life cycle assessment modeling

The approach of modeling all the unit processes of the electricity generation plant was adopted because it was then possible to track emissions associated with each unit process of the plant. The model was created using the MS Excel Spreadsheet (trademark of Microsoft) and then transferred to the LCA software of GaBi 4.4, which is a software product of PE International, Germany.

4 Results

In the following discussion on modeling results, the no capture scenario will serve as the baseline, and the differences between the no capture versus the retrofit and capture scenarios will be shown as percentage changes. Compared to the power output from an electrical generating station without capture, there is a 5.5 % decrease in power output in the retrofit scenario and a 33 % decrease in power output in the capture scenario due to the additional auxiliary power consumed by the FGD and CO_2 capture units. Therefore, additional coal is needed in order to compensate for this loss in power production. The results showed that an extra 5.8 % of lignite coal for the retrofit and an extra 48.6 % of lignite coal for the capture scenarios are needed.

The results from the four LCIA methodologies are summarized in Figs. 2, 3, 4, and 5. In each figure, the impact of the retrofit and capture scenarios on each environmental category is presented in terms of percentage change compared to the no capture scenario.

The contribution of each process to the results was also analyzed. In the next section, the results from application of the TRACI methodology are presented, and some sample results are summarized in Fig. 6.

Table 3 Boundary Dam Power Station characteristics

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
Gross capacity, MW	66	66	150	150	150	300
Gross cycle heat rate, kJ/kWh	12,500	12,900	10,500	10,400	10,800	9,900
Capacity factor, %	72.61	82.36	59.14	88.85	84.30	83.89

Table 4 Modeling assumptions

	ESP	FGD	CO_2 capture and compression
Particulate removal efficiency, %	99	70	50
CO_2 removal efficiency, %	–	–	90
SO_2 removal efficiency, %	–	99	99.5
SO_3 removal efficiency, %	25	50	99.5
HCl removal efficiency, %	–	90	95
NO_2 removal efficiency, %	–	–	25
Hg^{2+} removal efficiency, %	7.5	25	80
Auxiliary power requirements, % MW_{gross}	6.9[a]	3.8	34.6

[a] Auxiliary power requirements for the boiler and ESP operations

4.1 Global warming

The four methodologies of TRACI, IMPACT2002+, CML, and EDIP 97 showed highly consistent results of global warming potential (GWP). The GWP was reduced by 9.7 % in the retrofit scenario and by 80.5 % in capture scenario. In the no capture scenario, 97 % of GHG emissions originated from the electricity generation station operations and only 3 % from coal mining. In the retrofit scenario, 96 % of GHG emissions originated from electricity generation station operations and 4 % from coal mining. In the capture scenario, 74 % GHG emissions came from electricity generation station operations and 26 % from coal mining.

The main substances that contribute to GWP are CO_2, methane, and nitrous oxide. The GHG emissions from the coal mining process substantially increased in the capture scenario due to (1) an increase in the coal consumption by almost 50 %[1] and (2) a decrease in the GHG emission from electricity generation station operations by 90 % due to CO_2 capture. Environmental impact due to construction of the electricity generation station and the CO_2 unit was less than 1 % in all three scenarios.

4.2 Acidification

It can be seen from the results generated by the three methods of TRACI, CML2001, and EDIP 97 that there was a reduction of acidification impact in the retrofit and capture scenarios compared to the no capture scenario.

The results from the TRACI method showed 6.1 and 49.9 % reduction in the retrofit and capture scenarios, respectively. In the no capture scenario, 97.1 % of the acidification potential originated from the electricity generation station operations and only 2.9 % from coal mining. In the retrofit scenario, 96.7 % of the acidification potential originated from the electricity generation station operations and 3.3 % from coal mining. In the capture scenario, approximately 91 % of the acidification potential came from the electricity generation station operations and 9 % from coal mining. The main substances that contribute to acidification are ammonia (NH_3), SO_2, NO_x, NO_2, and NO.

The results from other methods showed reductions of acidification potential 6.5 and 50.3 % and 4.7 and 35.8 % in the retrofit and capture scenarios for CML2001 and EDIP 97, respectively. The reason for this reduction in acidification was due to removal of the SO_2 from the exhaust flue gases in the flue gas desulfurization unit, which was installed prior to the CO_2 capture unit. Since the MEA-based CO_2 capture process is very sensitive to SO_2, the SO_2 concentration that enters the CO_2 absorber needs to be less than 10 ppmv. In this research, 99 % of SO_2 has been removed from the flue gas before it entered the CO_2 capture unit.

The IMPACT2002+ method has two impact categories: aquatic acidification and terrestrial acidification/nitrification. Therefore, it generated different results from the other methodologies. The IMPACT2002+ method showed that the impact to aquatic acidification increased by 309 and 544 %, respectively, in the retrofit and capture scenarios, and the impact to terrestrial acidification/nitrification increased by 2.8 and 19 % in the retrofit and capture scenarios.

In the retrofit and capture scenarios, there may be direct impacts from the mine itself with drainage from the mine, i.e., water to water. Moreover, most of the SO_2 and other acid pollutants are removed by ESP and FGD instead of being emitted to the air. They are collected with bottom ashes and deposit in soil when landfilled and then transported from soil to water as a secondary effect. Thus, the impacts on acidification are transferred from the air to the soil and water. Therefore, the IMPACT2002+ methodology showed a substantial

Table 5 Carbon dioxide capture model assumptions

Parameter	Value
MEA concentration in sorbent, %	30
Lean sorbent CO_2 loading, mole CO_2/mole MEA	0.2
Temperature of the flue gas entering the CO_2 absorber, C	50
Desired CO_2 product pressure, psig	2,000
MEA losses, kg MEA/tonne CO_2	1.36077
Reclaimer waste, kg/tonne CO_2 captured	3.2
Activated carbon consumption, kg C/tonne CO_2 captured	0.075
Caustic consumption, kg NaOH/tonne CO_2 captured	0.13
Ammonia formation, kg NH_3/tonne CO_2	0.136
Water consumption, tonne/MWh	1.1
Sorbent regeneration heat requirement, kJ/kg	3,600
Enthalpy of steam, kJ/kg steam	2,000
Reboiler efficiency, %	85
Steam requirement, kg/MWh	2,045

[1] Note: Constant electricity output scenario was used in the study.

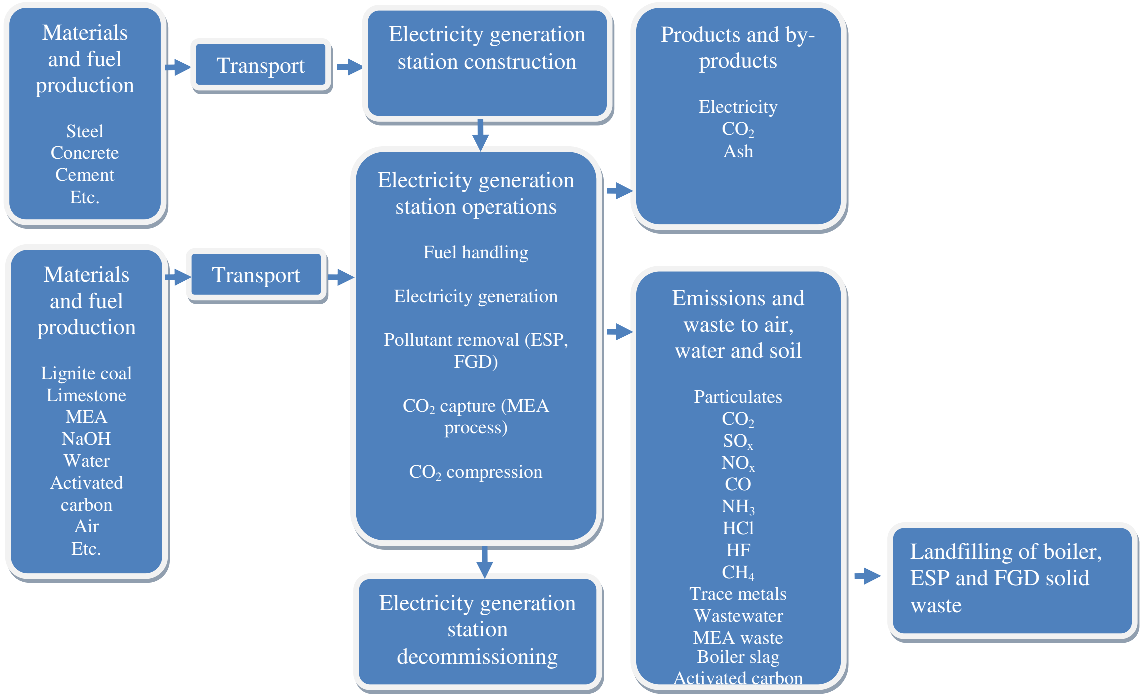

Fig. 1 System boundary for lignite-fired electricity generation station with post-combustion CO_2 capture

increase as it address the impacts of acidification in water and soil, while the other three methodologies showed a decrease as they address the impacts of the acidification to air.

4.3 Eutrophication

In TRACI, the observed increase in eutrophication in the air impact category was 7.7 % in the retrofit and 63 % in the capture scenario. In the no capture scenario, 95.7 % of the eutrophication potential was derived from coal mining and 4.21 % from the electricity generation station operations. In the retrofit scenario, 95.8 % of the eutrophication potential originated from the electricity generation station operations and 4 % from coal mining. In the capture scenario, approximately 96 % of the eutrophication potential came from the electricity generation station operations and 3.8 % from coal mining. Primarily due to the loss in plant capacity, NO_x emissions increased with the addition of a capture unit. In addition, the emissions of NH_3, MEA, and ethylene from the production of MEA also contributed to an increase in the

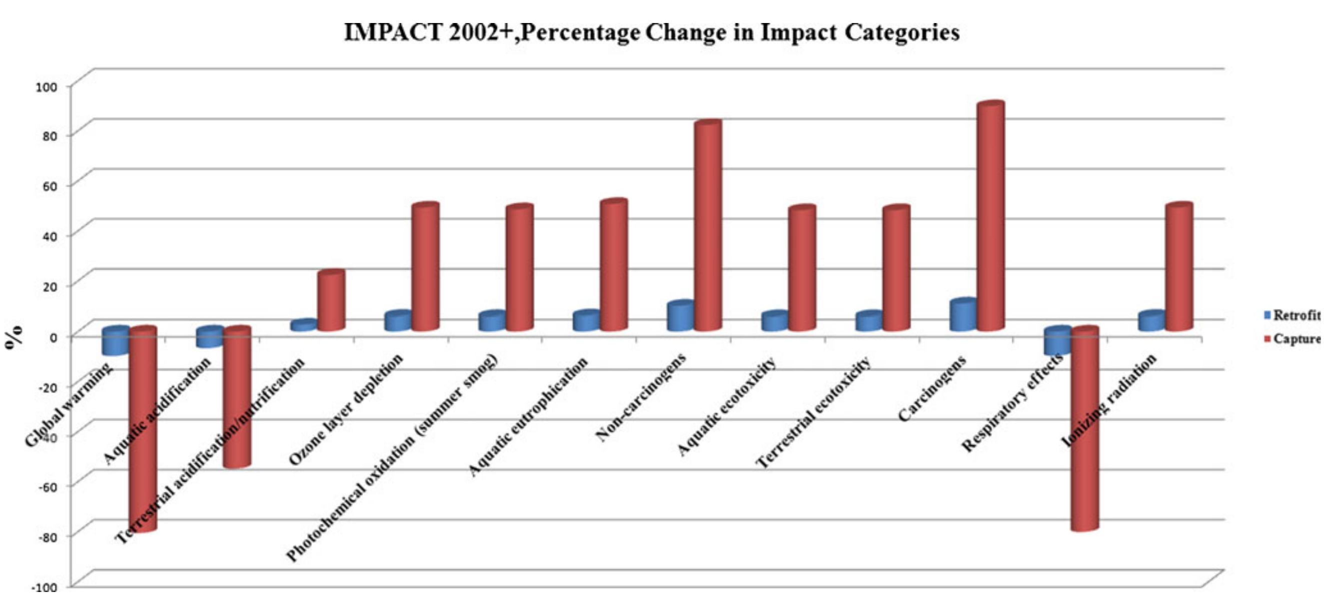

Fig. 2 Overall results from IMPACT2002+ methodology

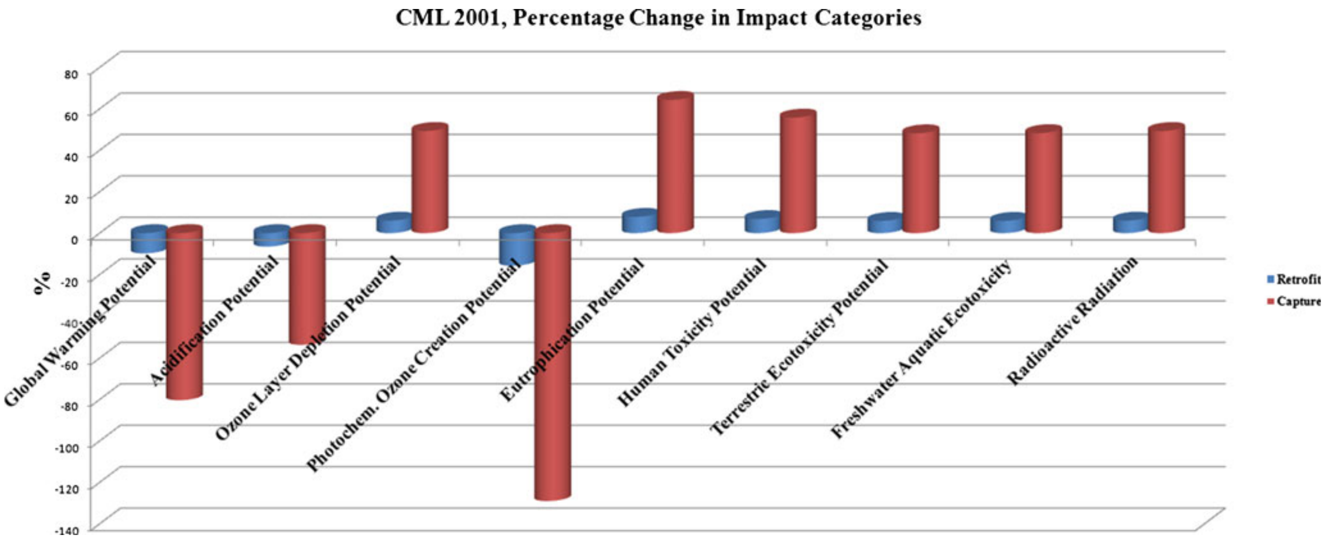

Fig. 3 Overall results from CML2001 methodology

eutrophication potential. An efficient way to reduce the amount of MEA loss and NH_3 emission in the absorber column is to install a water wash.

In CML2001, the increase in the eutrophication impact was 7.8 % in the retrofit and 64.3 % in the capture scenario. The results from the IMPACT2002+ method indicated that the potential for aquatic eutrophication was increased by 6.2 % in the retrofit scenario and by 51 % in the capture scenario. By contrast, the CML2001 method represents eutrophication in different media (soil, air, or water) as one category of nutrient enrichment potential impact, and the decrease in this category was approximately 2 % in the retrofit and 20 % in the capture scenario.

4.4 Ozone depletion

The results from all four methods showed that the potential for ozone depletion was increased by 6 % in the retrofit and 49 % in the capture scenarios compared to the no capture scenario. In TRACI, in three capture scenarios, almost 100 % of the ozone depletion originated from coal mining. The main substances that contributed to the increase in ozone depletion are R 11 (trichlorofluoromethane), R 114 (dichlorotetrafluoroethane), R 12 (dichlorodifluoromethane), and R 13 (chlorotrifluoromethane). The increased likelihood of ozone depletion was mainly due to the additional and multiple processes associated with the production and operation of the CO_2 capture system, which required crude oil and natural gas as inputs.

4.5 Ecotoxicity

4.5.1 Ecotoxicity water

The results of aquatic ecotoxicity impact generated from all four methods of TRACI, IMPACT2002+, CML2001, and EDIP 97 showed the same increasing trend in the retrofit

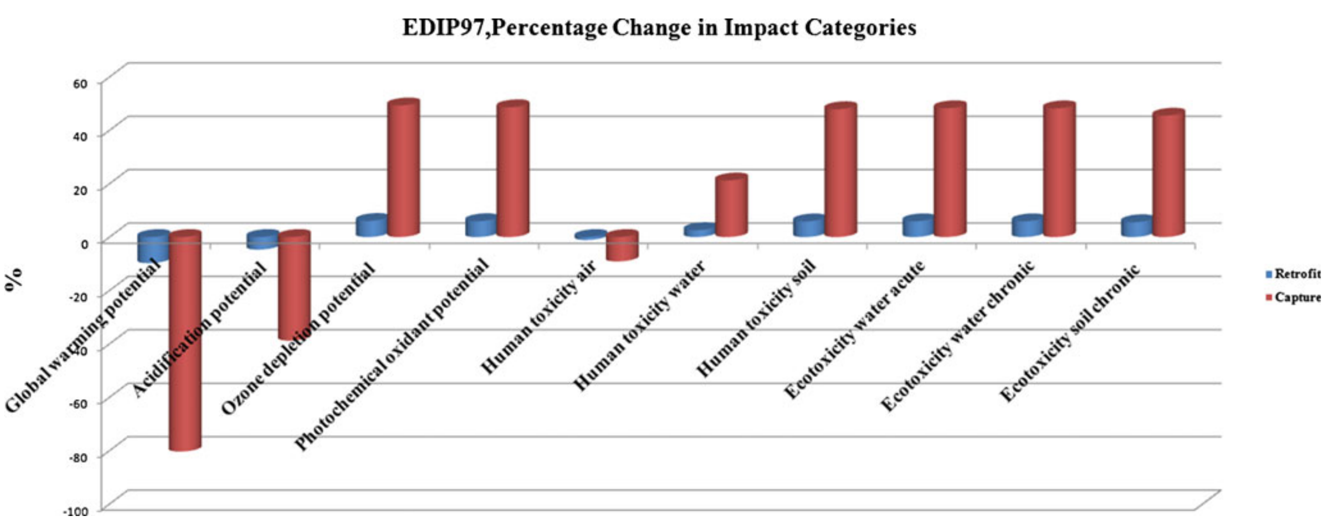

Fig. 4 Overall results from EDIP 97 methodology

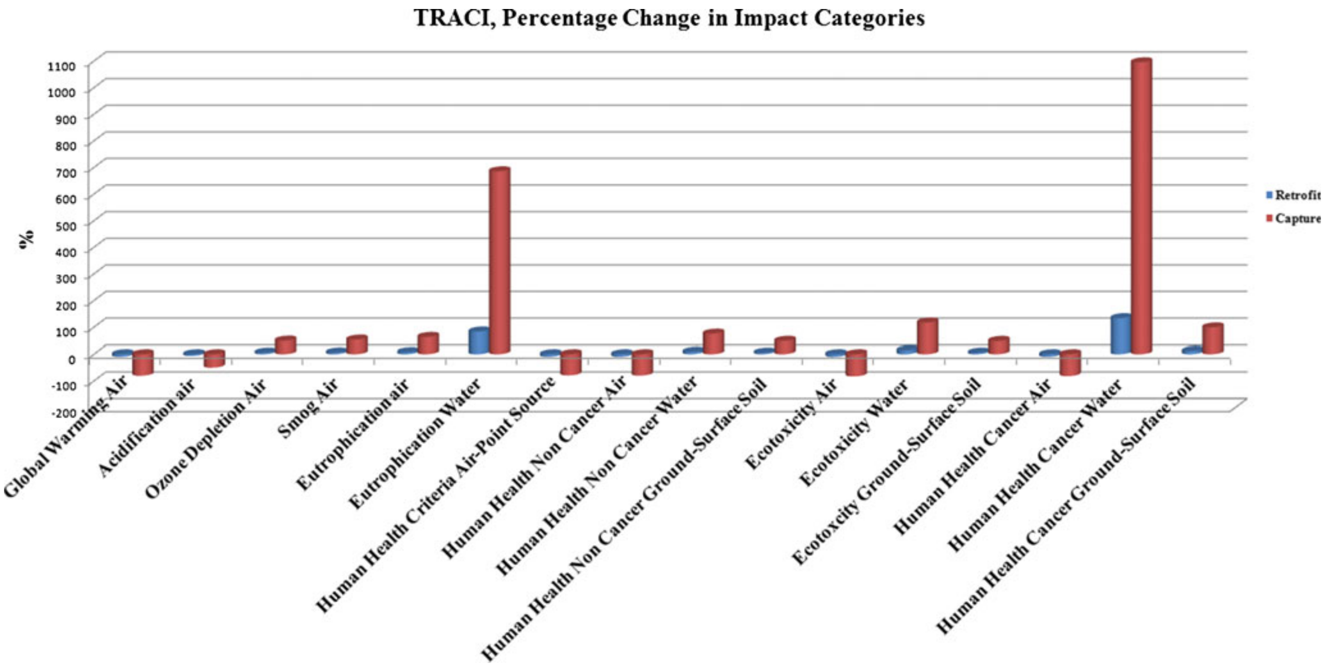

Fig. 5 Overall results from TRACI methodology

and capture scenarios compared to the no capture scenario. From the TRACI and IMPACT2002+ methods, the increase in the ecotoxicity water impact category was 14.3 % and 5.9 % in the retrofit and 117 % and 48.2 % in the capture scenarios, respectively. This increase was mainly due to the removal of heavy metals from the flue gas streams, which are shifted from the air to the soil and water. The significant reduction of heavy metals released to the atmosphere resulted from the capture of SO_2 and CO_2 compounds by the flue gas desulfurization unit and the CO_2 capture unit. As well, the wastes from the FGD and electrostatic precipitator (ESP) are deposited at landfills, which can eventually affect soil and groundwater. As a consequence, an increase in aquatic ecotoxicity was observed. In the CML2001 and EDIP 97 methods, the results showed an increase in freshwater aquatic ecotoxicity. This can be caused by the leaching from the landfill sites which contain trace elements. The emission of trace metals to river and groundwater and to air contributed to the impact category of ecotoxicity water.

4.5.2 Ecotoxicity air

TRACI is the only method that has an ecotoxicity air impact category. The result showed that the ecotoxicity to air was reduced by 10.3 % in the retrofit scenario and by 82.8 % in the capture scenario. In both no capture and retrofit scenarios, 4–5 % of the contributions were derived from coal mining, 93–94 % from electricity generation station operations, and 1.6–1.8 % from construction of the electricity generation station. In the capture scenario, 36 % was contributed by coal mining, 12 % by construction of the electricity generation station, and 48 % by operations of the electricity generation station. This reduction was mainly due to the retention of heavy metals in the FGD and CO_2 capture units.

4.5.3 Ecotoxicity ground surface soil

All four methods showed that the potential for ecotoxicity to ground surface soil increased in the retrofit and capture scenarios. The results from TRACI, IMPACT2002+, and CML2001 indicated that the potential for terrestrial ecotoxicity was increased by 5.9 % in the retrofit scenario and by 48.2 % in the capture scenario. The results from EDIP 97 indicate that the potential was increased by 5.5 % in the retrofit scenario and 45.5 % in the capture scenario.

In TRACI, the operation of the electricity generation station was the primary source for terrestrial ecotoxicity in all three scenarios. The trace elements were the main contributors to the increase of ecotoxicity in ground surface soil. The majority of trace elements in the flue gas were removed by the ESP and FGD systems. These trace elements became ash at the boiler bottom. The substances in the ash leached to the soil and then to the groundwater when it was landfilled. The trace elements caused an increase in the impact categories of toxic effect in soil (ecotoxicity to ground surface soil), which can have cancerous effect to humans (called the category of human health cancer ground surface soil) or no cancerous effect to humans (called the human health noncancer ground surface soil impact category). The impacts to the human health categories are further discussed in Section 4.6.

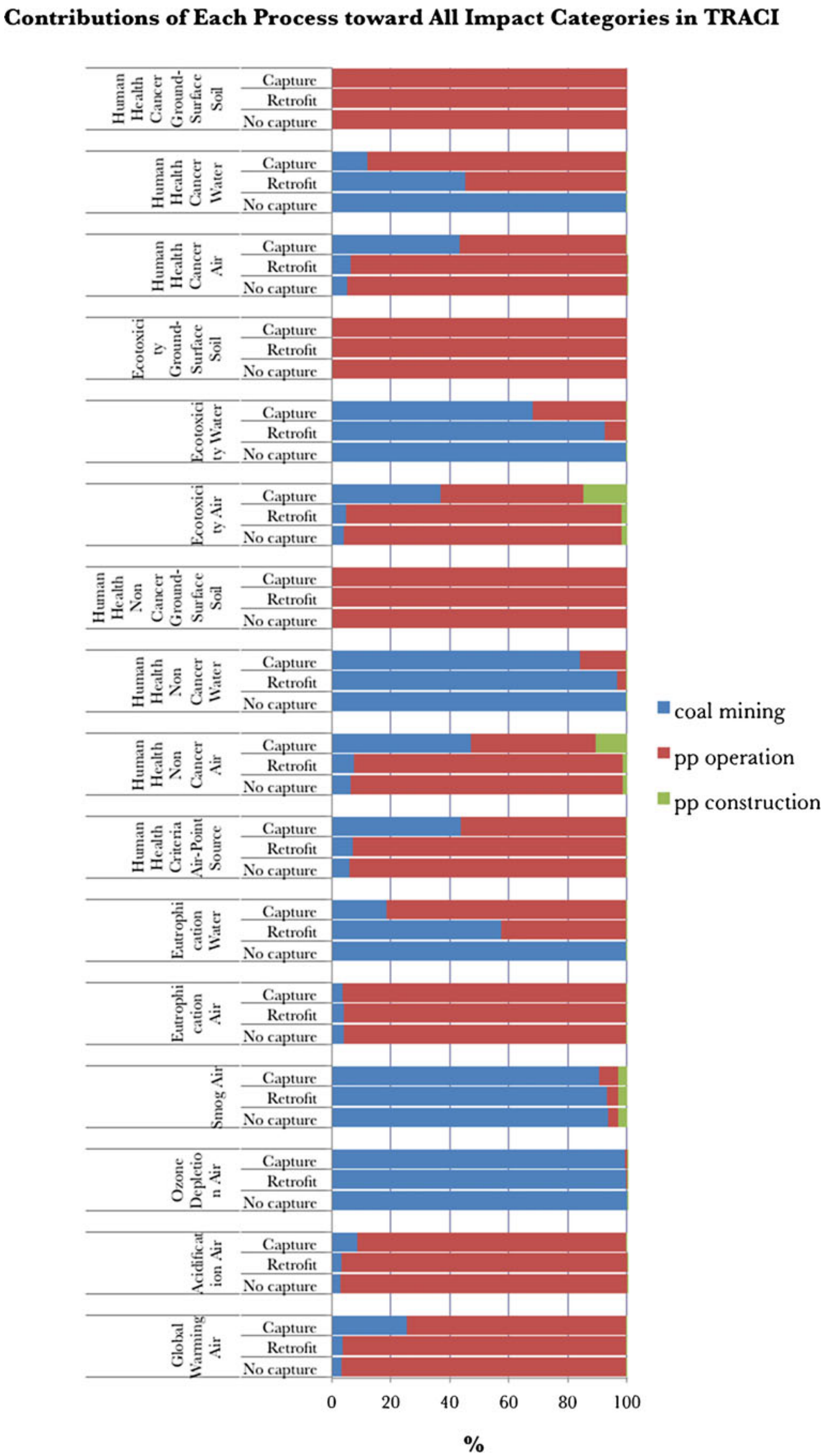

Fig. 6 Results from TRACI methodology: contributions of each process toward all impact categories

4.6 Human toxicity

In TRACI, the same emissions and sources impact the categories of human health cancer air and human health noncancer air. The release of heavy metals, volatile organic compounds (VOCs), and different inorganic emissions to air from electricity generation station operations contributed to these two impact categories. The amount of emissions released to the atmosphere was decreased due to the reduction of heavy metals in the FGD and CO_2 capture unit. The decrease in human health cancer air impact category was approximately 10 % in the retrofit and 82 % in the capture scenarios. In addition, the decrease in human health noncancer air impact category was approximately 10 % in the retrofit and 80 % in the capture scenarios. In EDIP 97, there were decreases in human toxicity air impact category by 1 % in retrofit and 9 % in capture scenarios. In CML2001, the human toxicity potential was increased by 7 and 56 % in the retrofit and capture scenarios, respectively. In IMPACT2002+, the increase in noncarcinogens impact category was approximately 10 % in the retrofit and 82 % in the capture scenarios. The increase in the carcinogens impact category was approximately 11 % in the retrofit and 90 % in the capture scenarios.

The trace elements from ash deposited at the boiler bottom will leach to the soil and contribute to the increase in the categories of human health noncancer ground surface soil and human health cancer ground surface soil. In TRACI, the impacts to the category of human health noncancer ground surface soil were increased by 6 % in the retrofit and 48 % in the capture scenarios. The impacts in the category of human health cancer ground surface soil were mainly from the construction of the electricity generation plant. In TRACI, the impacts to the category of human health cancer ground surface soil were increased by 12 % in the retrofit and 99 % in the capture scenarios. The results of EDIP 97 showed that the impacts to the human toxicity soil impact category were increased by 6 % in the retrofit and 48 % in the capture scenarios.

In case of the human health noncancer water and human health cancer water impact categories, the impacts came mostly from coal mining. There was an increase in these impact categories from the no capture to the capture scenarios. The increase in the human health noncancer water impact category was approximately 9 % in the retrofit and 76 % in the capture scenarios. In addition, the increase in the human health cancer water impact category was approximately 134 % in the retrofit and 1095 % in the capture scenarios. In EDIP 97, the increase in the human toxicity water impact category was 3 % in the retrofit and 21 % in the capture scenarios. The substantial increase is due to two reasons. Firstly, the coal consumption is much higher in retrofit and especially capture scenarios. Secondly, the majority of heavy metals and VOC are captured in the FGD and CO_2 capture unit and then leak to water after the landfill process.

4.7 Air-point source (TRACI)/respiratory effect (IMPACT2002+)

The results from TRACI showed a decrease in the impact category of human health criteria air-point source of 9.6 and 79 % in the retrofit and capture scenarios, respectively. In the

Table 6 Overview of the four LCIA methods (adapted from Table 4.4 in Manuilova (2011))

LCIA methods	CML2001	IMPACT2002+	TRACI	EDIP 2003
Country	Europe	Europe	USA	Europe
Characteristics	Site specific	Site dependent	Site dependent	Site dependent
Impact categories	11 midpoint categories: acidification eutrophication freshwater aquatic ecotoxicity marine aquatic ecotoxicity terrestrial ecotoxicity ozone layer depletion photochemical ozone creation global warming radioactive radiation abiotic depletion human toxicity	14 midpoint categories: ozone layer depletion global warming photo chemical oxidation aquatic acidification terrestrial acid/nitrification aquatic eutrophication aquatic ecotoxicity terrestrial ecotocixity human toxicity land occupation respiratory effects ionizing radiation non-renewable energy mineral extraction 4 damage categories: human health ecosystem quality climate change resources	12 midpoint categories: ozone depletion global warming smog formation acidification eutrophication human health cancer human health noncancer human health criteria pollutants eco-toxicity fossil fuel depletion land use water use	8 midpoint categories: global warming ozone depletion photochemical ozone formation acidification nutrient enrichment human toxicity ecotoxicity

no capture scenario, the operations of the electricity generation station contributed 94 % of the impact and coal mining contributed only 6 %. In the retrofit scenario, the operations of the electricity generation station contributed 93 % of the impact and coal mining contributed 7 % of the impact. In the capture scenario, the electricity generation station operations contributed 56 % of the impact and coal mining contributed 44 %. The decreased impact in the air-point source category can be attributed to the removal of PM in the FGD and CO2 capture units, which translated to a reduction of both primary and secondary particulate sulfate emissions (PM_{10}, $PM_{2.5}$, and SO_2) to the environment.

In the case of the respiratory effect, the main contributors were particulate matter ($PM_{2.5}$ and PM_{10}), NO_x, NH_3, SO_2, and VOC. The emission of these substances from the CO_2 capture unit at the electricity generation plant may pollute local and transboundary areas. In IMPACT2002+, the impact on respiratory effects for the capture scenario was decreased by 9.7 and 78 %, respectively, compared to the retrofit and the no capture scenarios.

4.8 Ionizing radiation (IMPACT2002+) and radioactive radiation (CML2001)

The results of IMPACT2002+ showed that the impacts to the ionizing radiation category were increased by 6 % in the retrofit and 40 % in the capture scenarios compared to the no capture scenario. The modeling results from IMPACT2002+ showed the same trend as those from CML2001.

4.9 Smog air

The results from TRACI show that coal mining contributes to the smog air impact category and accounted for 93.6, 93.1, and 90.5 % of the impact in no capture, retrofit, and capture scenarios, respectively. The result shows a percentage contribution from coal mining. The results expressed in specific units showed that the contribution of coal mining in the smog air impact category actually increases from no capture to capture scenarios. On the other hand, the operations from the electricity generation station contribute 3.4, 3.94, and 6.38 % to this impact category in the no capture, retrofit, and capture scenarios, respectively.

5 Discussion

The four LCIA methodologies use different midpoint reference substances for the same impact categories. For example, the category of acidification air in TRACI uses mole H+ equivalent as the reference substance. However, the methodologies of IMPACT2002+, CML2001, and EDIP 97 use kilogram SO_2-equivalent as the reference substance for the acidification potential impact categories. Both reference substances constitute primary causes for acidification. For the category of ozone depletion, TRACI and IMPACT2002+ use kilogram CFC-11-equivalent as the reference substance, while CML2001 and EDIP 97 use kilogram R11-equivalent. For the ecotoxicity water impact category, each LCIA methodology uses a different reference substance, which includes kilogram 2,4-dichlorophenoxyace (TRACI), kilogram TEG-equivalent (IMPACT2002+), kilogram DCB-equivalent (CML2001), and cubic meter water (EDIP 97). Among the four methodologies, some other impact categories that adopt different midpoint reference substances include ecotoxicity air, ecotoxicity soil, eutrophication, photochemical oxidation, and human toxicity (Table 6).

Despite the fact that the four LCIA methodologies use different reference substances and different mechanisms to calculate the results, their generated results demonstrate similar trends. They all showed an increase in the retrofit and capture scenarios compared to the no capture scenario in the impact categories of eutrophication air, ecotoxicity water, ecotoxicity ground surface soil, eutrophication water, human health cancer ground surface soil, human health cancer water, human health noncancer ground surface soil, ozone depletion air, human health noncancer water, and ionizing radiation. The results also show reductions in the impact categories of acidification, human health criteria air-point source, human health noncancer air, ecotoxicity air, global warming, human health cancer air, and respiratory effects. The reductions can be attributed to the capture of particulate matter, trace elements, CO_2, and acid gases such as SO_x, NO_x, HCl, and HF in the ESP, FGD, and CO_2 capture units. However, since the captured trace elements from the bottom ash are likely to eventually leach to soil and then to the groundwater when landfilled, an increase in the impact categories associated with soil and water was observed. As well as the higher impact in eutrophication can be attributed due to the NH_3 and MEA emission and the ethylene emission from the production of MEA. The same trends of impacts for each environmental category can be observed from the results of the four methodologies shown in Figs. 2, 3, 4, and 5.

6 Conclusions

As mentioned earlier, the research objective is to conduct a LCA study of a Canadian lignite-fired electricity generation station with and without post-combustion CO_2 capture and evaluate the three scenarios of (1) no CO_2 capture (no capture), (2) partially (retrofit), and (3) fully integrated CO_2 capture (capture). The LCA study sheds light on the environmental performance of an implementation of the CO_2 capture technology from a full life cycle perspective. The secondary objective is to evaluate the different LCIA methodologies and, based on the comparison,

provide recommendations on a LCIA methodology best suited for the Canadian environment. A number of observations related to the research objectives can be drawn from the study, and they are discussed as follows.

The methods of TRACI, IMPACT2002+, CML2001, and EDIP 97 were selected for evaluation in this study because they are the most comprehensive and commonly used LCIA methodologies. Moreover, they are all midpoint approaches so that an unbiased comparison of the results can be made. Since the four LCIA methodologies assess impacts based on different units, the percentage change of the impacts for each category was calculated and compared against the results for the no capture scenario. The comparison reveals that the results from all the four methods of TRACI, IMPACT2002+, CML2001, and EDIP 97 showed similar trends for most impact categories even though they use different reference substances and assessment mechanisms. Compared to the no capture scenario, substantially less GHG emission is evident in the retrofit and "CO_2 capture" scenarios. However, the processes and operations associated with the CO_2 capture system required additional energy and material consumption, which increased the environmental impacts in the categories of eutrophication to air and water, aquatic and terrestrial ecotoxicity, human health, and ozone depletion air. It can be observed that the environmental impact was shifted from the air compartment to the soil and water compartments in the retrofit and capture scenarios. Compared to the no capture scenario, the retrofit and capture scenarios also have less impacts in the categories of acidification air, human health air, and ecotoxicity air. The CO_2 capture system reduced the harmful emissions to the air, while the solid waste components were deposited to the industrial landfill. However, some substances in the solid waste will eventually leach to the soil and then to the groundwater.

The characteristics of the emissions and wastes generated by a carbon capture technology play an important role in determining the LCIA methodology to be adopted for a LCA study of that technology. Since the primary emissions from the post-combustion CO_2 capture process include CO_2, SO_2, NO_x, NH_3, VOC, HCl, HF, and heavy metals, which have greater impacts on the categories of global warming, acidification, human toxicity, and eutrophication than on other categories, we believe that a LCIA methodology adopted in a LCA study on the post-combustion CO_2 capture process should emphasize these four categories. For example, NO_x, SO_2, and VOC are the major components contributing to the category of human toxicity, and NO_x, SO_2, HCI, and HF are the major substances that cause acidification.

In this study, the number of subcategories defined in each category reflects the level of granularity in analysis and is used for evaluating the extent of emphasis assigned to that category. Compared to CML2001 and EDIP 97, TRACI and IMPACT2002+ put greater emphasis on the categories of human toxicity, acidification, and eutrophication because they specify detailed impacts on different factors in each category. For example, CML2001 defines human toxicity as one category, and it does not distinguish the compartments of air, soil, and water and the aspects of human health. Although CML2001 includes the category of marine aquatic ecotoxicity, it is not applicable for the present LCA study because the province of Saskatchewan is located at the middle of a continent and far from the sea. A weakness of EDIP 97 is that it does not have the eutrophication impact category, which means it cannot account for the nitrogen compounds that are important emissions from the electricity generation and CO_2 capture processes. By contrast, TRACI defines six subcategories under the human toxicity categories, which support detailed consideration of the environmental impacts to air, water, and soil, as well as the carcinogenic and noncarcinogenic effects. Similarly, the IMPACT2002+ method adopts different categories for aquatic acidification versus terrestrial acidification. With more subcategories defined, more detailed information can be specified in the LCA study so that the sources for environmental impacts can be identified and improvements can be made to a particular phase of the CO_2 capture process system.

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